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FUSION TECHNOLOGY INSTITUTE

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ABSTRACT

The SOMBRERO inertial fusion reactor conceptual design study is of a 1000 MWe KrF laser driven near symmetric illumination system which utilizes a Li_2O solid breeder moving bed in a blanket made entirely of low activation carbon/carbon composite material. The Li_2O particles flow through the various parts of the blanket under gravity, then are transported through an intermediate heat exchanger and around the loop in a fluidized state by helium gas at 0.2 MPa. Liquid lead is used in the intermediate loop, going to a steam generator and a double reheat steam power cycle. There are 60 beams in the near symmetric illumination configuration. The laser energy is 3.4 MJ, the target gain 118 and the rep-rate 6.7 Hz. At the midplane, the blanket thickness is 1 m giving a tritium breeding ratio of 1.25 and an overall energy multiplication of 1.08. The first wall is at 6.5 m radius and is protected from x-rays and ions by 0.5 torr of Xe gas. Grazing incidence metallic mirrors are located at a distance of 30 m and dielectric final focusing mirrors at 50 m from the target. Source neutrons are directed into neutron traps located in line with the grazing incidence mirrors. The final focusing mirrors which are out of line of sight of source neutron are subjected to low energy scattered neutrons only and can survive the 30 full power year reactor lifetime. The Li_2O particles enter the chamber at 550°C and exit at an average temperature of 740°C, giving a power cycle efficiency of 47%. The gross power output is 1360 MW and for a 7% laser efficiency, the driver power is 325 MWe, with the remaining 35 MWe used for auxiliary equipment. The chamber and shield qualify for near surface burial as Class A waste while the Li_2O breeder, as Class C waste.

I. INTRODUCTION

The SOMBRERO study is part of the inertial confinement fusion comparison effort initiated by the Office of Magnetic Fusion in October of 1990. In this effort, two teams, one headed by W. J. Schafer Associates and the other by McDonnel Douglas have been working on KrF laser and heavy ion beam driven IFE reactors. SOMBRERO is the W. J. Schafer Associates team's reactor design utilizing a KrF laser driver.

Solid breeding materials are in the forefront of efforts around the world for use as breeding materials in fusion reactors. Research and development programs in the US, Japan and Europe have been in place for many years and there is a wealth of data available on them. Properly selected, solid breeders offer the potential for high temperature operation, low activation, greatly improved safety, as well as freedom from corrosion and corrosion transport issues which are concerns with liquid metal systems. Solid breeder blankets have been proposed for ITER (International Thermonuclear Engineering Reactor) by the US, EC and Japan, and have been used in the ARIES series of commercial reactor design.

However, most of these designs have solid breeding materials in a static configuration. Such designs have problems which have to do with high pressure coolants, typically He gas at 5-8 MPa and require a second He gas loop for T_2 extraction. Temperature control is difficult because it depends on thermal conductivities of materials and interface gaps which change with temperature cycling and radiation, in unpredictable ways. Furthermore, static solid breeder blankets suffer from issues of Li burnup, phase changes, swelling and hot spots. The concept of moving beds eliminates all of these problems, since the material is both breeder and coolant. Because the material spends a large fraction of the time outside the reactor, its makeup and configuration can be continuously monitored and reconstituted, eliminating problems of Li burnup and particle attrition. At the low velocities envisioned for the moving bed, wall erosion is not a concern. Finally, a He gas pressure of only 0.2 MPa is needed to fluidize and transport the particles around the loop. This alone, if nothing else, makes the solid breeder moving bed system exceedingly attractive and distinguished it from all the other solid breeder He gas cooled designs.

Such a scheme has been proposed for tokamaks[1] but has not been taken seriously due to the geometric limitations of the magnet system. It has also been used in SOLASE,[2] a CO_2 laser driven IFE reactor design (1977), at a time when all the pertinent characteristics of Li_2O were not well known. More recently, a moving bed of solid particles was used in CASCADE,[3] an IFE reactor with a rotating reaction chamber resembling a cement mixer, a design appropriate only for indirectly driven targets.

There are some issues with moving beds that have to be

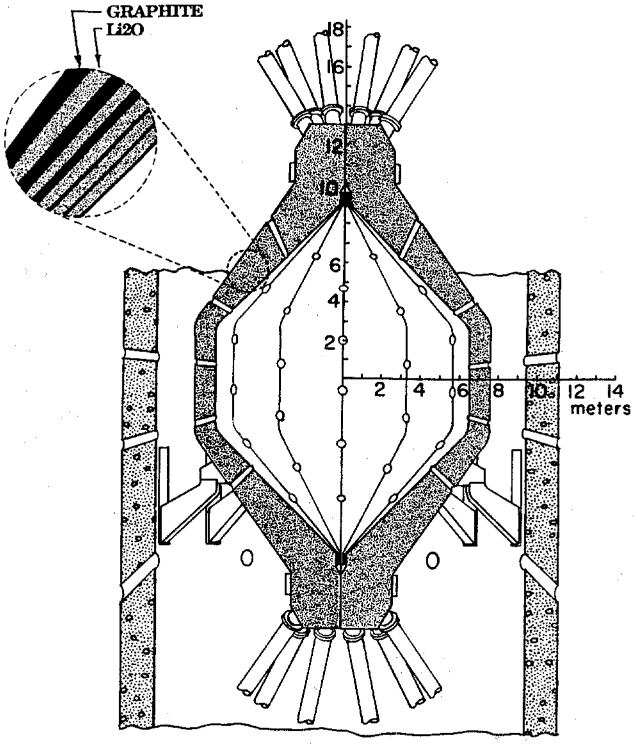

Fig. 1. Cross section of SOMBRERO reactor.

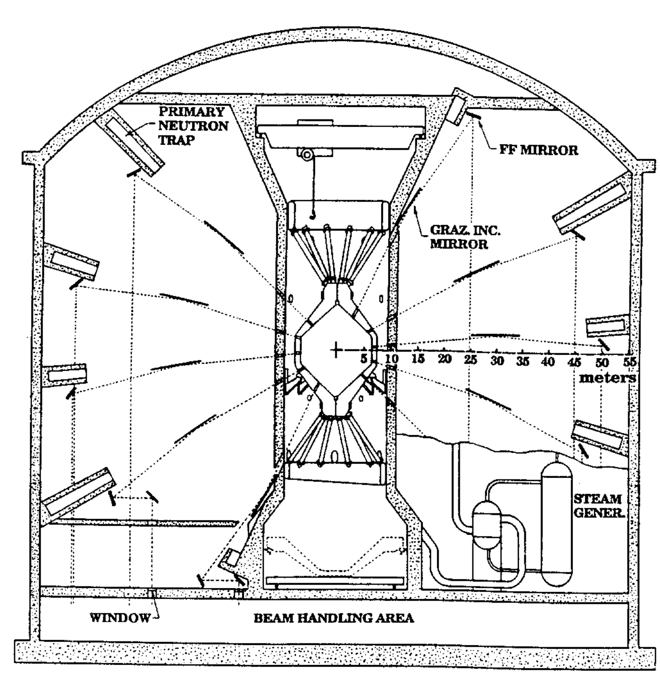

Fig. 2. Side view of containment building.

dealt with. Since such designs always fall into the dry wall category, the chambers are large ($\leq$ 6.5 m) and the inventory of Li_2O, when the material in the whole loop is included, is very big. Although there is a wealth of information on fluidized beds, there is little information on heat transfer in moving beds. Some large scale experiments are needed to verify the heat transfer coefficients which have been scaled from small experiments.[4]

This paper describes the chamber design, neutronics, thermal hydraulics, tritium analysis and safety. The KrF laser design,[5] balance of plant[6] and a report devoted entirely to safety issues of SOMBRERO[7] are among companion papers in these proceedings.

II. OVERALL DESCRIPTION

The present conceptual design study, SOMBRERO, is of a 1000 MWe IFE reactor driven with a 3.4 MJ KrF laser utilizing 60 beams in a near symmetric configuration. A target gain of 118 is used and at a rep-rate of 6.7 Hz gives a DT fusion power of 2688 MW. The beams are distributed along the surfaces of 10 cones with the vertex at the target. There are six beams in each cone and the polar angles for the five cones in the upper half of the chamber are 25.84°, 45.57°, 60°, 72.54° and 84.25°, and the lower half has five cones with complementary angles. Figure 1 is a cross section of the chamber showing the beam ports lying on ten horizontal planes where the sides of the cones intersect the sides of the chamber. The chamber itself consists of 12 wedge shaped modules assembled together and are totally independent of each other with separate supply and return tubes. It has a vertical cylindrical central section with conical ends, and has a radius of 6.5 m at the midplane and an overall height of 18 m. It is entirely constructed of a carbon/carbon composite and the internal passages are sealed with a thin coating of SiC. Each module is subdivided both radially and circumferentially, with the carbon fraction increasing from the front at 3% to the rear at 50%. This arrangement incorporates a reflector which does not require separate cooling. The beam ports are built into the sides of the modules, half a beam port in each side. In this way the profile of the ports within the internal flow channels is considerably reduced. The first wall (FW) thickness is 1.0 cm, and at the midplane the cooling channel behind it is 7 cm deep, increasing to 37 cm at the extremities, making the flow area constant along the entire FW from top to bottom. This is done to ensure a constant velocity at the FW where a high heat transfer coefficient is needed.

The Li_2O particles with a size range of 300-500 μm have a void fraction of 40% in the moving bed and the grains themselves are 90% of theoretical density. They are admitted at the top from a manifold which doubles as a cyclone separator, to disengage the carrier He gas from the particles. After the particles enter the chamber they flow under the force of gravity through the chamber and exit at the bottom. The velocity at the FW is 1.15 m/s. Each succeeding zone has progressively lower velocities toward the rear of the blanket. The inlet temperature to all the zones is 550°C, but the outlet temperature is 700°C at the FW, while in the rear zones it is 800°C. The total mass flow rate of 2×10^7 kg/hr has an equilibrated outlet temperature of 740°C. Flow control in the different zones is accomplished with control baffles located at the bottom of the chamber to ensure that there will be no voids anywhere in the nuclearly heated

TABLE I

Relevant SOMBRERO Reactor Parameters

Laser energy (MJ)	3.4
Target gain	118
Reactor rep-rate (Hz)	6.7
Fusion power (MW)	2688
Reactor energy multiplication	1.08
Tritium breeding ratio	1.25
Blanket thickness at midplane (m)	1.0
Thermal power (MW)	2903
Power cycle efficiency (%)	47
Gross electric power (MWe)	1364
Laser efficiency (%)	7
Laser power (MWe)	325
Net electric power (MWe)	1000

zones.

After going through the chamber, the particles are transported around the loop and through the intermediate heat exchanger (IHX) in a fluidized or entrained state by He gas at 0.2 MPa. This very low He gas pressure will exist in the chamber which will unavoidably have a trickle of gas flowing countercurrent to the particles. This small amount of gas flow in the chamber aids in maintaining a steady movement of the particles and prevents the formation of clustering or compaction. A thin coating of SiC on the inner surface of the chamber flow channels aids in sealing the c/c composite structure against He gas leakage into the chamber. The FW is protected from x-rays and ions by 0.5 torr of Xe gas.[8] Since the beam ports are open onto the chamber enclosure, the whole containment building also has 0.5 torr of Xe gas. A certain amount of He leakage into the building can be tolerated without degrading the reactor performance. Innovative ideas for separating He from Xe such as diffusion membranes must be incorporated into the Xe recycling system.

The chamber is surrounded by a cylindrical shield composed of 70% concrete, 20% steel and 10% He coolant. It has an inner radius of 10 m and is 1.7 m thick. The chamber modules are supported on retractable beam elements cantilevered from the shield. Holes in the shield line up with holes in the chamber to allow laser beams to reach the target in the center of the chamber. The containment building is shown in Fig. 2. It has a radius of 55 m and an overall height of 115 m. The beam handling area is located on the lowest level. Each beam is directed to a specific spot in this lower level, where it is reflected vertically, passing through a window in the floor of the building. The beam then goes to a final focusing (FF) mirror located at 50 m from the target which directs it onto a grazing incidence metallic mirror (GIMM) and finally through the beam ports into the chamber. The GIMMs are at a distance of 30 m from the target and bend the beams by 6°. This makes it possible for the FF mirrors to be out of line of sight of the primary neutrons. The primary neutrons are directed into neutron traps, consisting of concrete cylinders with conical holes which have a high aspect ratio. Neutronic evaluations show that holes with aspect ratios of > 2 will effectively trap most of the neutrons, allowing a negligible amount of low energy neutrons to backscatter. This makes it possible for the FF mirrors, which are coated with a dielectric, to be lifetime components. The GIMMs are subjected to source neutrons and their lifetime will depend on the fluence limit and on the degree of damage recovery upon annealing.

Reactor maintenance will be covered in Ref. 6 of these proceedings. In one scenario, individual reactor modules are separated from the chamber and lowered into the pit below by an overhead polar crane. To do this, the supply and return Li_2O tubes are removed and the module support retracted into the shield. A polar carriage is used to support the lowered module and lay it down horizontally (see Fig. 2), after which it is transported radially out of the containment building into a maintenance facility. Table I gives the relevant SOMBRERO parameters.

III. NEUTRONICS

Neutronics calculations for SOMBRERO were performed using a point source at the center of the chamber emitting neutrons and gammas with energy spectra determined from target calculations for a generic single shell target. Spherical geometry has been assumed using the ONEDANT code with neutron cross sections based on the ENDF/B-V evaluation.

The overall tritium breeding ration (TBR) is 1.25 and the overall reactor energy multiplication is 1.08. For the DT power of 2688 MW, the total thermal power is 2903 MW, with 803 MW deposited at the FW surface by x-rays and ion debris, and the remainder deposited volumetrically by the neutrons and gamma photons. The peak FW power density is 10.9 W/cm^3 and the peak blanket power density is 12.6 W/cm^3, both occurring at midplane. Peak dpa and helium production rates in the graphite are 15.3 dpa/FPY and 3770 He appm/FPY, respectively. Based on this, the FW is expected to have a 5 FPY lifetime.

A 1.7 m thick shield wall surrounds the reactor at a radius of 10 m. Holes in this shield allow the laser beam to reach the target in the center of the chamber. Neutronic calculations show that this shield, which consists of 70% concrete, 20% steel and 10% He coolant makes it possible to perform hands-on maintenance in the space between it and the outer containment building wall following reactor shutdown. This is important, since all the final focusing and grazing incidence mirrors, as well as the IHX and steam generators are located in this space. It has also been determined that the required wall thickness directly exposed to source neutrons must be 3.2 m, while the cumulative shield behind the blanket, 2.73 m. This means that the outer building wall need only be 1.0 m thick, taking into account the 1.7 m thick shield at the 10 m radius.

IV. LIFETIME OF FINAL OPTICS

The lifetime of the final focusing (FF) mirrors depends on the neutron fluence limit for the dielectrically coated or metallic mirror, the solid angle fraction subtended by the beam ports, damage recovery with annealing and the location of the mirror relative to the target. The solid angle fraction subtended by the 60 beam ports in SOMBRERO is only 0.25%. The neutron flux level at the grazing incidence metallic mirror (GIMM) located

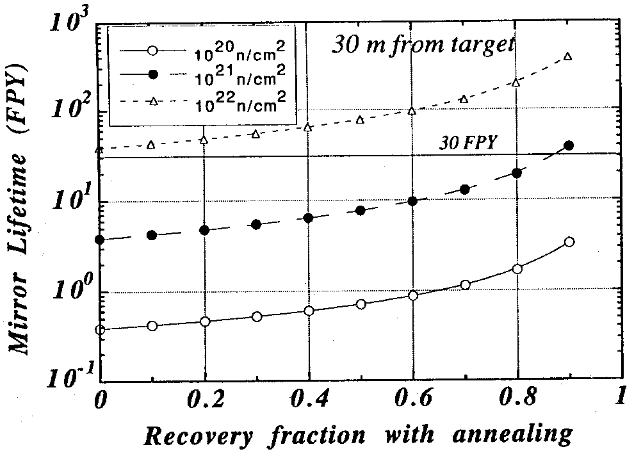

Fig. 3. Lifetime of metallic grazing incidence mirrors.

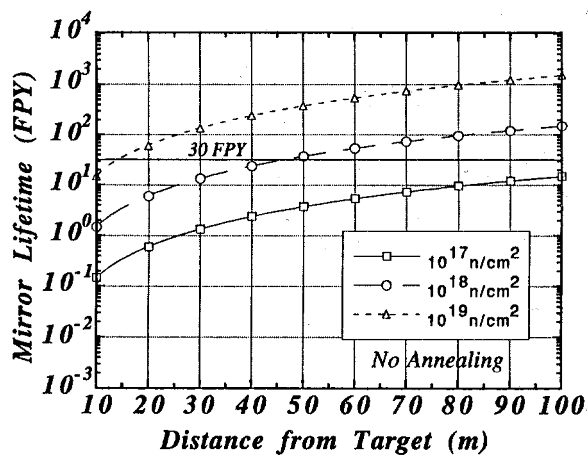

Fig. 4. Lifetime of dielectrically coated FF mirrors.

in the direct line-of-sight of the source neutrons at 30 m from the target has been determined to be 8.2×10^{12} n/cm^{2}s and is contributed mostly by the direct source neutrons. Figure 3 gives the lifetime for these mirrors as a function of the fast neutron fluence limit and the recovery fraction with annealing. It can be seen that a GIMM at 30 m from the target assuming an 80% annealing recovery, can have a lifetime of 20 FPY if the limit is 10^{21} n/cm^2. If the limit is 10^{22} n/cm^2, it can have a lifetime of 30 FPY with no annealing. Although the dielectrically coated mirrors are placed out of the direct line-of-sight of the source neutrons, secondary neutrons resulting from the interaction of the streaming source neutrons with the outer reactor building can cause significant radiation damage to the coating. To reduce the secondary neutron flux, the source neutrons are directed into high aspect ratio traps as shown in Fig. 2. As a result, the fast neutron flux (E > 0.1 MeV) at the dielectrically coated mirrors located at 50 m from the target was determined to be 8.6×10^8 n/cm^{2}s. The currently allowed fluence to dielectrically coated mirrors is 10^{18} n/cm^2. Figure 4 gives the lifetime of the FF mirrors as a function of fluence and distance from the target. At 10^{18} n/cm^2 the SOMBRERO FF mirrors will have a lifetime of 37 FPY if they are located at 50 m from the target.

TABLE II

Thermal Hydraulics Parameters

Li_2O in/out temp. at FW (C)	550/700
Li_2O in/out temp. in rear (C)	550/800
Li_2O equilibrated out temp. (C)	740
Li_2O mass flow rate (kg/s)	5590
Max. Li_2O velocity at FW (m/s)	1.15
Ht. trans. coeff. at midplane FW (W/m^{2}K)	2758
Max. steady state outside surf. temp. (C)	1485
Max. steady state inside surf. temp. (C)	1220
Liquid lead in/out temp. (C)	400/600
Lead mass flow rate (kg/s)	114,450
Lead pumping power (MW)	3.0

V. THERMAL HYDRAULICS

Heat transfer in moving beds is dominated by the effective thermal conductivity of the solid and interstitial gas instead of by the conductivity of the gas alone, as is the case in fluidized beds. To determine heat transfer coefficients it is necessary to know the effective viscosity of the moving bed. These were obtained from experiments performed at the University of Wisconsin,[4] in which Nusselt numbers were obtained as a function of velocity in electrically heated tubes for several ranges of solid particles from 100-600 μm made of soda-lime glass. The analytic expression obtained made it possible to extrapolate the effective viscosities to the velocity ranges relevant to SOMBRERO. With the effective viscosities in hand, as well as the effective thermal conductivities which depend on the materials and void fractions, and the specific heat of Li_2O, the Dittus Boelter formulation is used to obtain the heat transfer coefficients. Since Li_2O is harder than soda-lime glass, we expect the effective viscosities to be lower yet, making the heat transfer coefficients estimate conservative. At the FW, the heat transfer coefficient is 2758 W/m^{2}K for a velocity of 1.15 m/s and a channel depth of 7.0 cm. Finite element modeling has shown the maximum steady state temperature at the outside surface of the FW occurs at Z = 4.59 m and is 1455°C, and on the inside surface 1242°C. Everywhere else, the temperature of the structure is <800°C.

After leaving the chamber the particles are transported in a fluidized mode to the four IHX where they exchange heat with liquid lead. The Li_2O enters the IHX at 740°C, exits at 550°C while the lead enters at 400°C and exits at 600°C, after which it goes to a steam generator. The power cycle is a double reheat with steam at 538°C and 24 MPa giving a conversion efficiency of 47%. When they leave the IHX, the particles are lifted in an entrained mode by He gas to the upper manifold, to start the cycle all over. Table II gives the main thermal hydraulics parameters.

VI. TRITIUM CONSIDERATION

The predominant tritium species in the He carrier gas is maintained as HTO, by the addition of H_2O, so that a partial pressure of O_2 of 10^{-5} Pa is achieved. Under these conditions the partial pressure of T_2 will only be 2×10^{-6} Pa and the T_2 permeation at the steam generator is manageable. Since only $\sim$10% of the carrier gas goes through the IHX and a barrier factor of $\sim$100 exists on the steam generator tubes, the T_2 permeation rate through to the steam generator will be only $\sim$15 Ci/day. It is expected that a self replenishing oxide layer will exist on the steam generator tubes due to the O_2 in the steam. The H_2O partial pressure of 64 Pa in the He is far below the 3150 Pa needed to form LiOH(T) which would melt at 417°C and begin to agglomerate the breeder particles. Tritium in the form of T_2O and HTO is recovered from the carrier gas by adsorption on molecular sieves. The solubility of T_2 in the Li_2O at 650°C is $\sim$0.081 wppm, and for the 2000 tonnes of Li_2O, this is a T_2 inventory of $\sim$162 g.

VII. SAFETY ASSESSMENT

A summary of the safety analysis is given here and the details can be found in Ref. 7 of these proceedings. The biological dose rate in the space where the IHX and steam generators are located is low enough that hands-on maintenance can be performed 24 h after shutdown. The reactor chamber enclosure itself, however, will require remote maintenance. The chamber and shield qualify as Class A low level waste but the Li_2O as Class C shallow land burial waste. Routine atmospheric release of T_2 to the maximally exposed individual is 0.71 mrem/y for a site boundary 1 km from the point of release. This is far lower than the EPA effluent limit of 10 mrem/y. As a consequence of a highly unlikely series of simultaneous accident scenarios, the estimated maximum whole body dose is 2.11 rem, which is below the 5 rem level at which emergency evacuation plans are required. This very low off-site dose obviates the need for N-stamp nuclear grade components which can result in a substantial saving in capital costs.

VIII. CONCLUSIONS

The described KrF laser driven IFE reactor SOMBRERO utilizing a moving bed of Li_2O particles in a c/c composite chamber has many attractive features: low activation, low pressure, low T_2 inventory, straightforward T_2 recovery, makes use of the good features of solid breeders but not their problems, reasonably simple chamber design, credible maintenance, high power cycle conversion efficiency and a high degree of safety potential. It provides for hands-on maintenance in the area external to the primary shield within 24 hours after shutdown. Most importantly, there appears to be a credible solution for having final focusing mirrors which can survive the entire reactor lifetime. The metallic grazing incidence mirrors can have a lifetime of 20 FPY if 80% annealing recovery can be achieved and the radiation limit is 10^{21} n/cm^2.

On the debit side, the dry wall FW protection scheme using a Xe buffer gas ends up with a large chamber with a high Li_2O inventory. Inherent also in the KrF laser system using near symmetric illumination is a large containment building.

ACKNOWLEDGEMENT

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